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16. Abstract

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SUMMARY

Measurements of the external magnetic field of several electron-bombardment mercury ion thrusters were made using a single axis fluxgate magnetometer. Both permanent and electromagnet thrusters were included. The axial dipole moment accounted for most of the external field. In addition, residual fields from an electromagnet thruster were approximately 20 percent of the initial field. Simple degaussing of the axial electromagnets reduced the residual fields to 1 to 2 percent of the initial field.

INTRODUCTION

Electron-bombardment ion thrusters are being considered for a variety of space missions (refs. 1 and 2). Interactions between the thruster or thrusters and the spacecraft are of major interest (ref. 3). The magnetic field of the thruster(s) is one source of possible concern. These fields could interact with the spacecraft scientific package (ref. 4), and could possibly impact spacecraft attitude control (ref. 5).

Measurements of the magnetic field of several thrusters were made using a single axis fluxgate magnetometer. Data are presented for a 30-cm thruster which utilized permanent magnets for the magnetic field in the discharge region; a 30-cm thruster with the permanent magnets replaced with electromagnets; and a permanent magnet 5-cm thruster.

APPARATUS

Thrusters

The 30-cm diameter permanent magnet thruster was built by Hughes Research Laboratories (HRL) under contract NAS3-14140 (ref. 6). It utilized permanent magnets for the magnetic field of the discharge chamber which varied between about 1×10^{-3} to 4×10^{-3} tesla within the discharge chamber on the thruster axis A cutaway view of this thruster is shown in figure 1(a) and another view of the thruster without the groundscreen in figure 1(b).

The magnetic field in the discharge region arises from three sources for this thruster. Twelve axial permanent magnets are mounted parallel to the thruster axis (or Z axis of figure 1(a). One of these thin cylindrical magnets can be seen in figure 1(a) and five of them appear in figure 1(b). Eight radial permanent magnets were mounted perpendicular to the thruster centerline upstream of the propellant manifold. These can be seen in figure 1(b). A magnetic baffle also contributed to the magnetic field in the discharge region. This is an electromagnet that can be seen in figure 1(a).

An electromagnet thruster was built that was identical to the permanent magnet thruster except that the permanent axial and radial magnets were replaced by the same number of electromagnets. These radial and axial electromagnets were individually driven by two separate power supplies.

A 5-cm mercury electron-bombardment ion thruster built by Hughes Research Laboratories under contract NAS3-15483 (ref. 7) was also tested. It utilized four permanent axial magnets to produce the magnetic field in the discharge chamber. A photograph of the 5-cm thruster is shown in figure 2.

Magnetometer

A single-axis fluxgate magnetometer capable of measuring magnetic flux densities as small as a few tenths of a gamma (1 gamma = 10^{-9} tesla) was used. This magnetometer also had the capability of nulling out any steady ambient magnetic field up to 70,000 gammas

PROCEDURE

All of the magnetic field measurements were made in areas relatively free of magnetic material and during off shift hours to minimize the effect of transient extraneous magnetic fields. All magnetic field measurements were obtained using the following procedure:

After an initial 10-minute warmup for the magnetometer, the thruster was removed to a distance of approximately 15 meters from the magnetometer probe. The maximum field from the thruster at this point was less than 1 gamma. Any ambient fields were then nulled out. The thruster was then moved toward the probe either to a predetermined distance or until full-scale deflection was obtained on a particular range of the magnetometer. The corresponding field or distance was measured depending on which of the above two methods was used. This procedure was repeated a number of times to further reduce the uncertainties in the data. Most of the data points presented are the average of four measurements.

The effective axial dipole moment was determined by means of on-axis measurements that were taken both upstream and downstream of the thruster to account for any offset of the center of the effective dipole from the center of the thruster. The effective axial dipole moment, M (amp-meter^2), was obtained from the following relation

$$M = 5\times10^{6}\ r^{3}\ B \tag{1}$$

where B is the magnetic flux density in tesla at the distance r in meters.

With the electromagnet thruster, measurements of residual fields were made in the manner discussed above and also by shutting off power to the electromagnets once the thruster was in a fixed position. The effects of the leads and electromagnet power supplies on these measurements were tested and found to be negligible.

RESULTS AND DISCUSSION

Data taken for the permanent magnet thruster was presented in figure 3. The magnetic field parallel to the Z axis (B_Z) was measured both upstream and downstream on the thruster centerline (Z axis). Magnetic field measurements perpendicular to the thruster axis (radial direction, B_X) and in the plane of the accelerator grids were also made. The axial distance is the distance between the center of the probe and the center of the thruster (which is halfway between the backplate and grids), and the radial distance is the distance between the center of the probe and the thruster axis (Z axis).

An effective axial dipole moment for this thruster was obtained using equation (1) with all of the data on the thruster axis at distances greater than 1 meter and averaging the results. These data and calculated dipole moments are shown in table I. The amount of uncertainty in the data can be seen from this table. The average value from this data is 9.9 ± 0.4 amp-meter^2. Also this data shows that the center of the effective dipole moment is actually 8 cm upstream of the thruster center rather than at the center of the thruster itself.

The data in the radial direction (i.e., the component of B in the X or Y direction) serves mainly to show that fields in this direction are much smaller than fields in the axial direction at a comparable distance on the thruster axis. The field in this direction arises from three potential sources. The axial dipole has a component in the radial direction in the plane of the grids; similarly, any misalinement from perpendicular to the thruster axis introduces an unknown component of axial dipole; and the radial magnets themselves. The radial magnets should

tend to cancel each other out due to their symmetric arrangement in the thruster. A major contribution to the field in the radial direction is therefore from the axial dipole, and the magnetic environment of the thruster can to a good approximation be determined from the axial dipole moment alone.

The electromagnet thruster tested was an optimized version of the permanent magnet thruster. In a separate experiment the currents for each set of electromagnets were varied until optimum thruster performance was obtained. Most of the data were obtained at these optimized current levels. However, another reason for testing the electromagnet thruster was that by varying the sets of electromagnets independently, their relative contribution to the field at a point could be determined. These data and data on residual fields were also taken.

Figure 4 contains the magnetic flux density in the Z direction measured downstream on the electromagnetic thruster axis. The distances are measured from a point on the thruster 8 cm upstream of the thruster center. This was the center of the effective axial dipole for the permanent magnet thruster and should be nearly the same for this thruster. As shown in table II, this data leads to an effective average dipole moment of 21.5 ± 1.0 amp-meter^2. This reflects the fact that the magnetic field for the optimized electromagnet thruster was larger than the field for the unoptimized permanent magnet thruster.

It was found that varying the magnetic baffle had no detectable effect on the magnetic flux density at any points outside the thruster where measurements were made (i.e., >2 meters).

The radial magnets were also found to contribute less than 10 percent to the axial dipole moment. This is due to the weak coupling in the magnetic circuit of the thruster. A measurement in the radial direction of the magnetic flux perpendicular to the thruster centerline (B_X) was also made. This value was 22 gammas at a distance 2 meters from the thruster axis. This is approximately 5 percent of the value of the magnetic flux density in an axial direction on the thruster centerline (B_Z) at a comparable distance. As in the permanent magnet thruster, this field results from the same three sources. By turning off the power supply

for the radial magnets, it was determined that the radial electromagnets themselves contributed approximately 30 gammas to the field at this point while the other two sources, at least at this point, decreased the field to its value of 22 gammas with all the electromagnets on.

Measurements were also made of the residual fields when all of the electromagnets were shut off. These measured values were consistently about 20 percent of the values of the field with the magnets turned on. Through a simple procedure of reversing the current through the axial electromagnets and progressively lowering the maximum current level, it was possible to lower the residual fields to approximately 1 to 2 percent of the initial field.

Similar axial measurements on the 5-cm permanent magnet thruster led to an effective dipole moment of 2.36 ± 0.1 amp-meter^2. Data taken at 3 meters are presented in table III. Here the number of permanent magnets on the thruster was varied. The resulting dipole moments were linear with the number of magnets as expected.

CONCLUDING REMARKS

The external magnetic fields of the ion thrusters considered were found to be primarily due to the axial set of magnets. They accounted for over 90 percent of the axial dipole moment. The axial dipole moment also contributed to the magnetic field perpendicular to the thruster axis in planes other than the one through the center of the effective axial dipole. The radial magnets alone led to a dipole moment perpendicular to the thruster axis of less than 10 percent of the magnitude of the axial dipole moment. The magnetic environment of these thrusters to a good approximation could therefore be determined from the axial dipole moment alone. Efforts to reduce the magnetic field of a thruster should therefore center on reducing the effect of the axial magnets.

Residual fields from an electromagnet thruster were approximately 20 percent of the initial field. Simple degaussing of the axial magnets reduced the residual fields to 1 or 2 percent of the initial field.

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TABLE I. - MAGNETIC DIPOLE CALCULATION

FOR THE PERMANENT

MAGNET THRUSTER

Average distance, m	Magnetic flux density, T	M, amp-meter^2
5.60	1.0×10^{-8}	8.80
4.40	2.5×10^{-8}	10.32
3.48	5.0×10^{-8}	10.52
2.73	1.0×10^{-7}	10.20
1.97	2.5×10^{-7}	9.11
1.55	5.0×10^{-7}	9.32
1.30	1.0×10^{-6}	11.00
	Average	9.9 ± 0.4

TABLE II. - MAGNETIC DIPOLE CALCULATION

FOR THE ELECTROMAGNET THRUSTER

Distance, m	Magnetic flux density, T	M, amp-meter^2
8.2	6.5×10^{-9}	17.9
7.2	9.8×10^{-9}	18.4
6.2	1.65×10^{-8}	19.8
4.7	4.65×10^{-8}	23.9
3.95	7.1×10^{-8}	22.0
3.2	1.53×10^{-7}	25.1
2.2	4.45×10^{-7}	23.6
	Average	21.5 ± 1.0

TABLE III. - MAGNETIC DIPOLES

FOR THE 5-CM THRUSTER

Number of magnets	Magnet flux density at 3 meters, tesla	M, amp-meter^2
8	38.5×10^{-9}	5.20
6	26.5×10^{-9}	3.58
4	17.5×10^{-9}	2.36
2	8.5×10^{-9}	1.15
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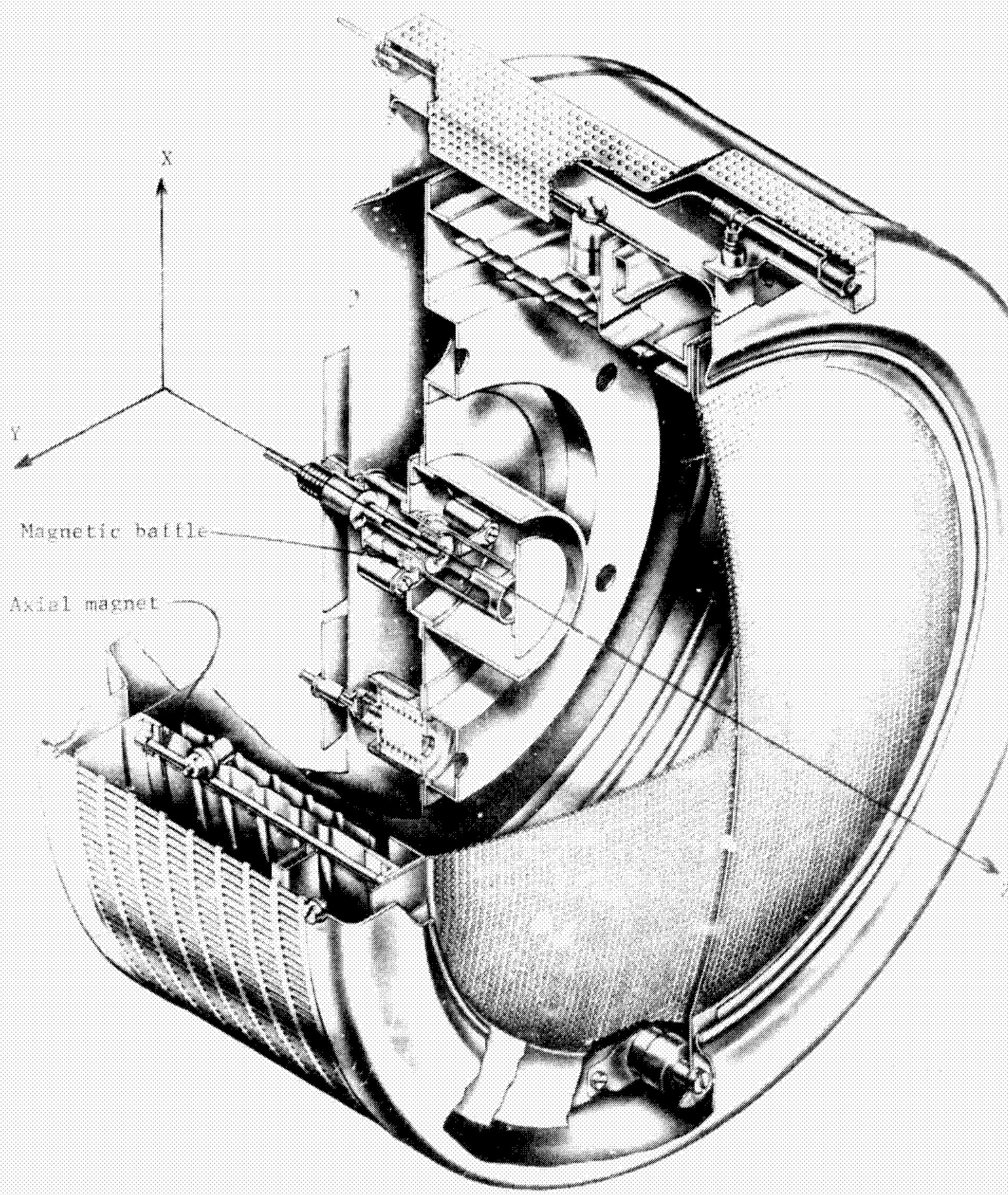
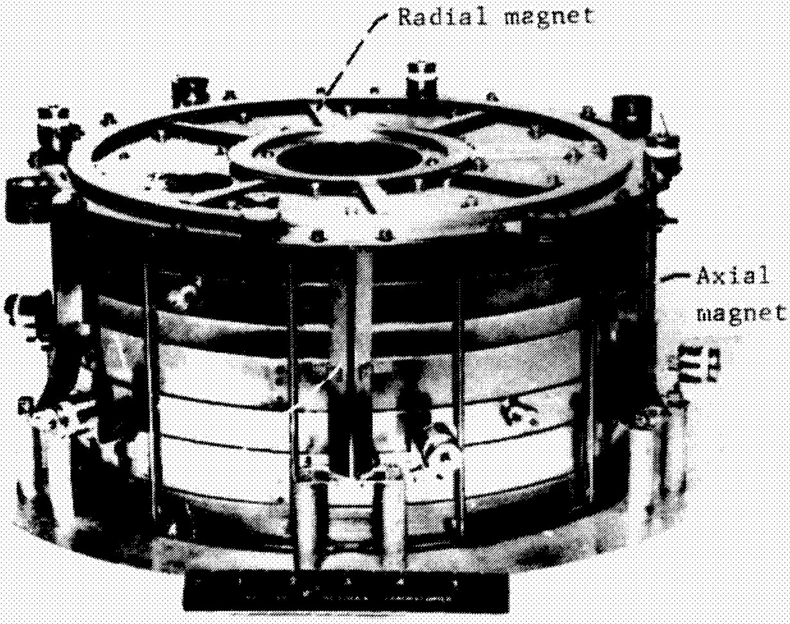


(a) With groundscreen.

Figure 1. - Thirty-centimeter permanent magnet thruster.



(b) Without groundscreen.

Figure 1. - Concluded.

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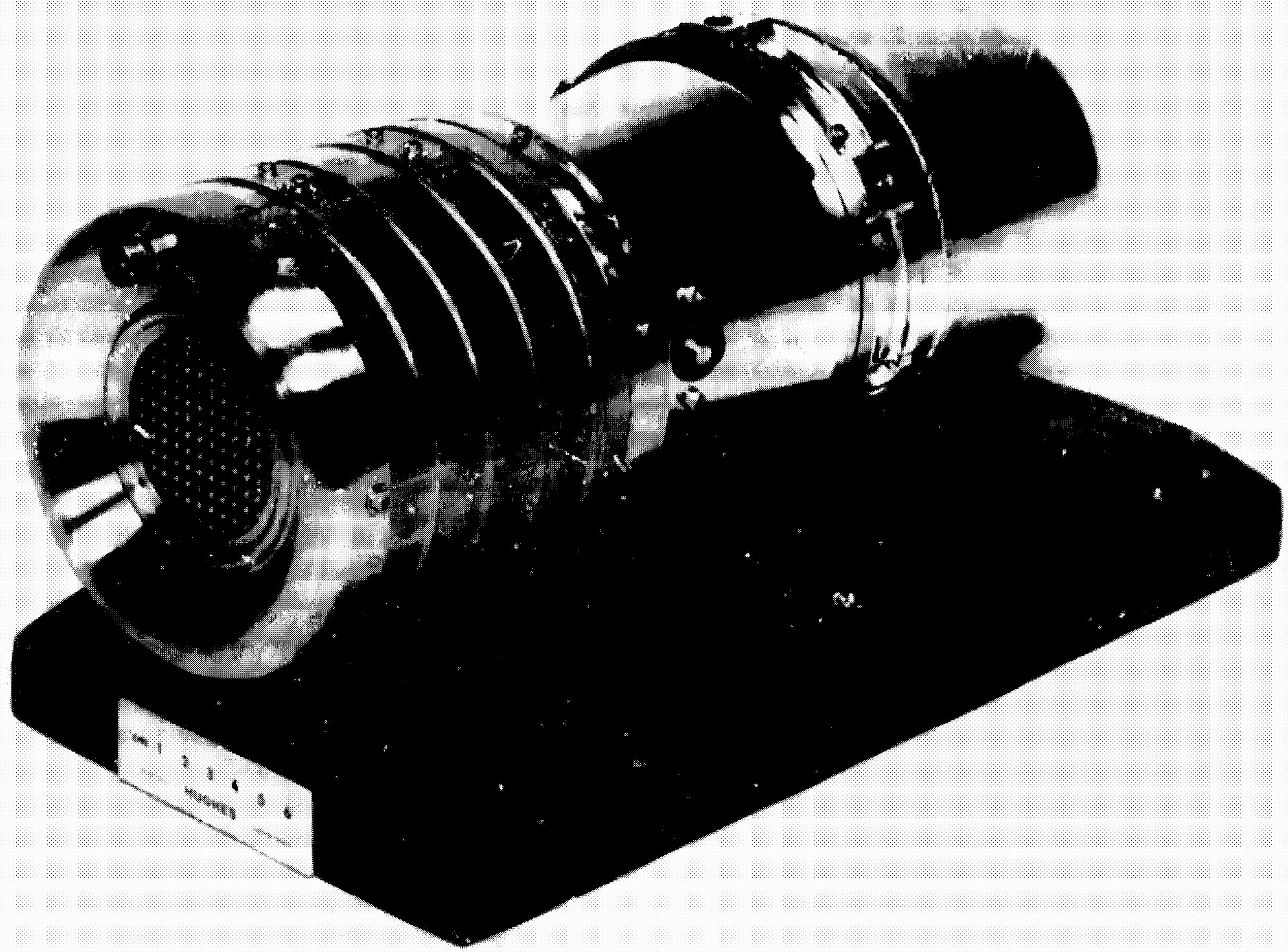

Figure 2. - Five-centimeter permanent magnet thruster.

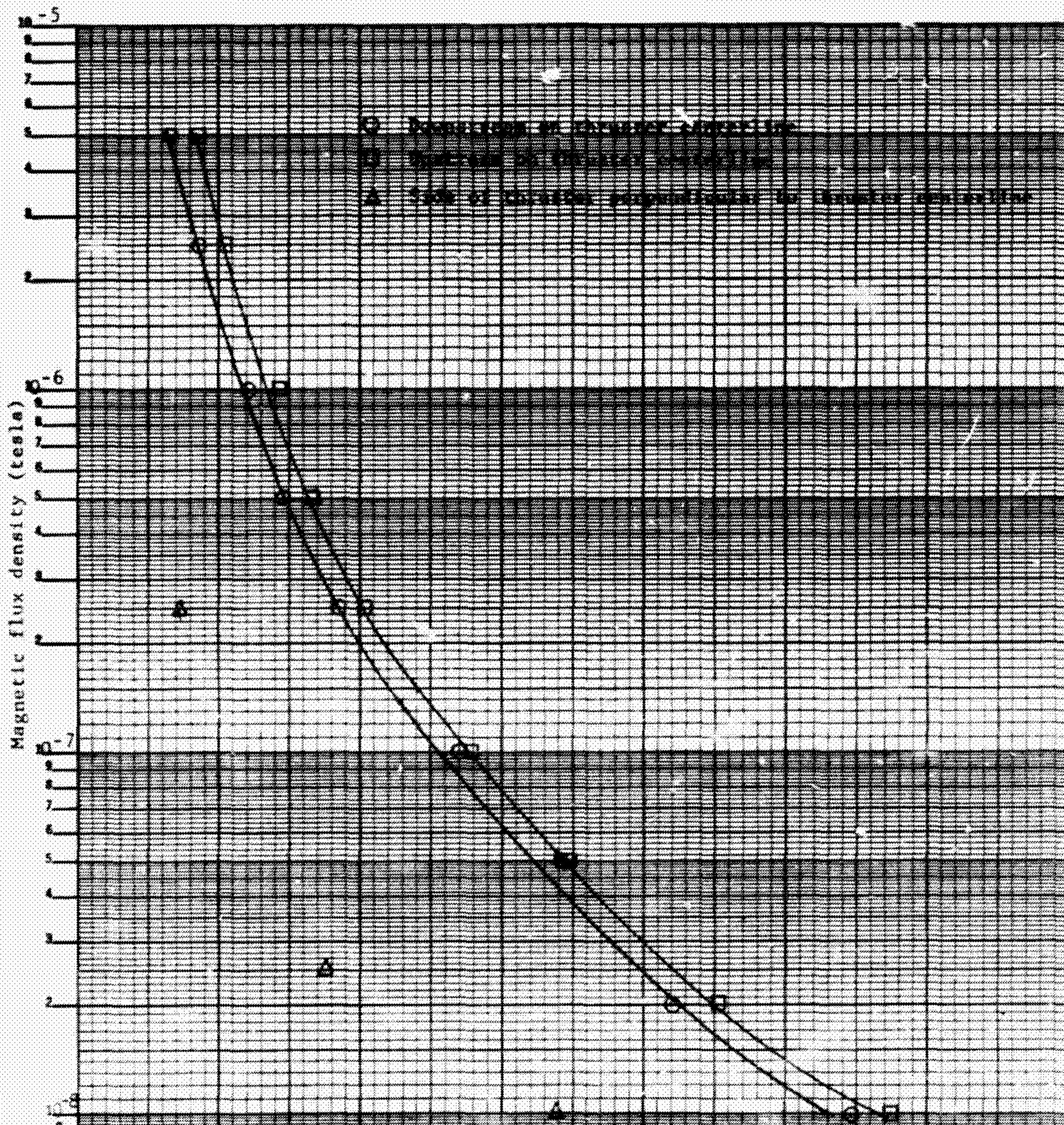

Figure 3. - Magnetic flux density for the permanent magnet thruster.

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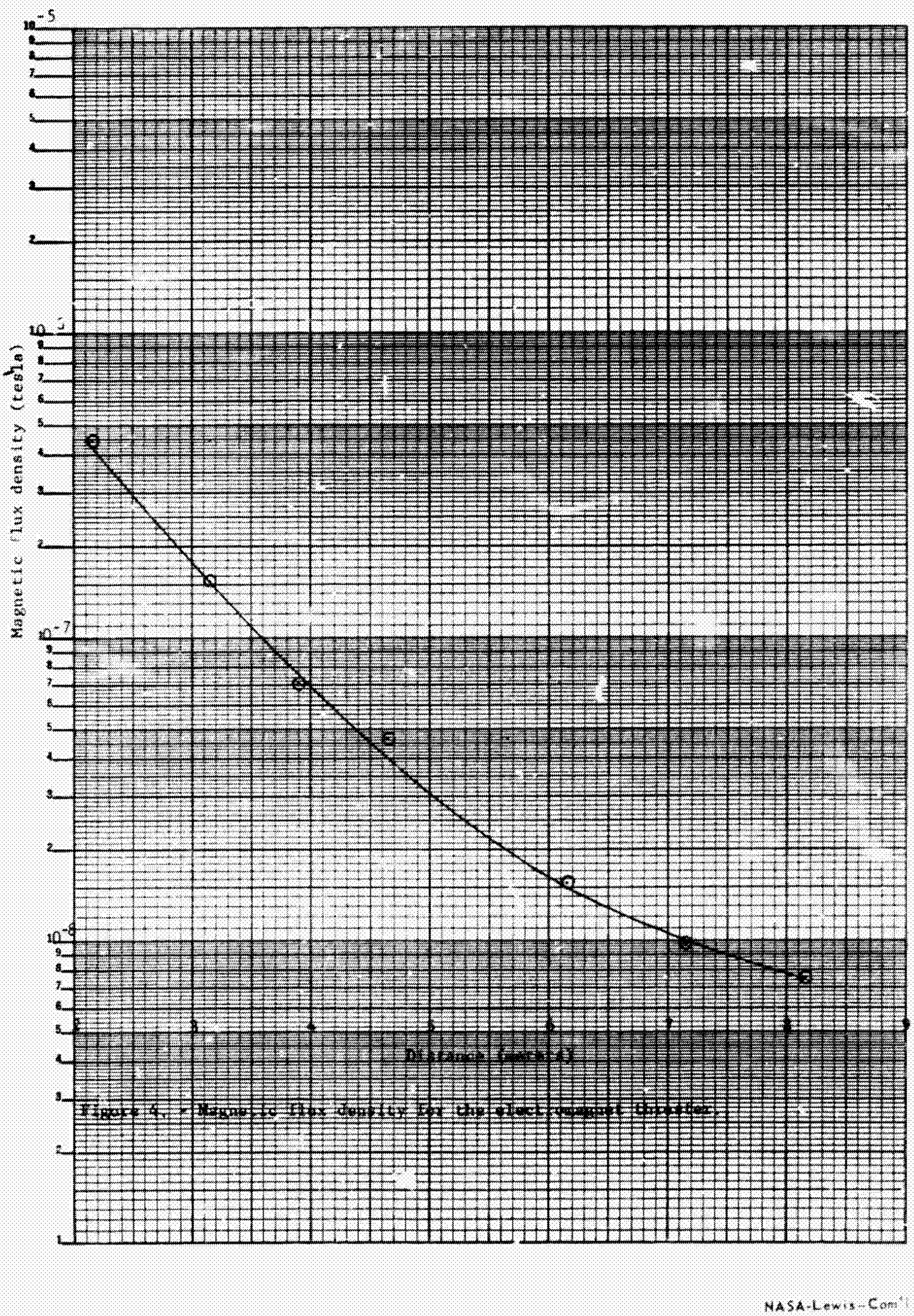

Figure 4. - Magnetic flux density for the electromagnet thruster.